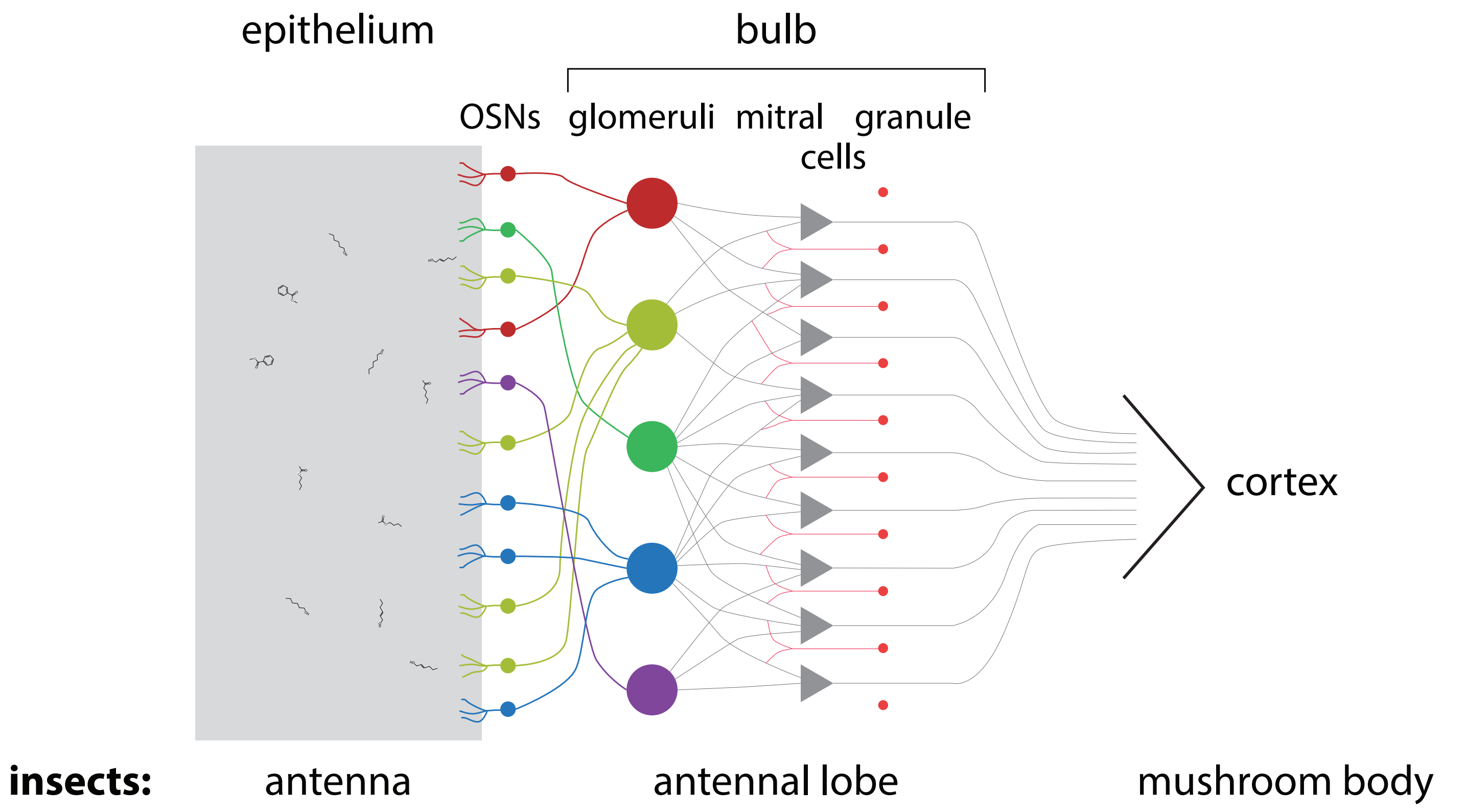
Environmental adaptation of olfactory receptor distributions

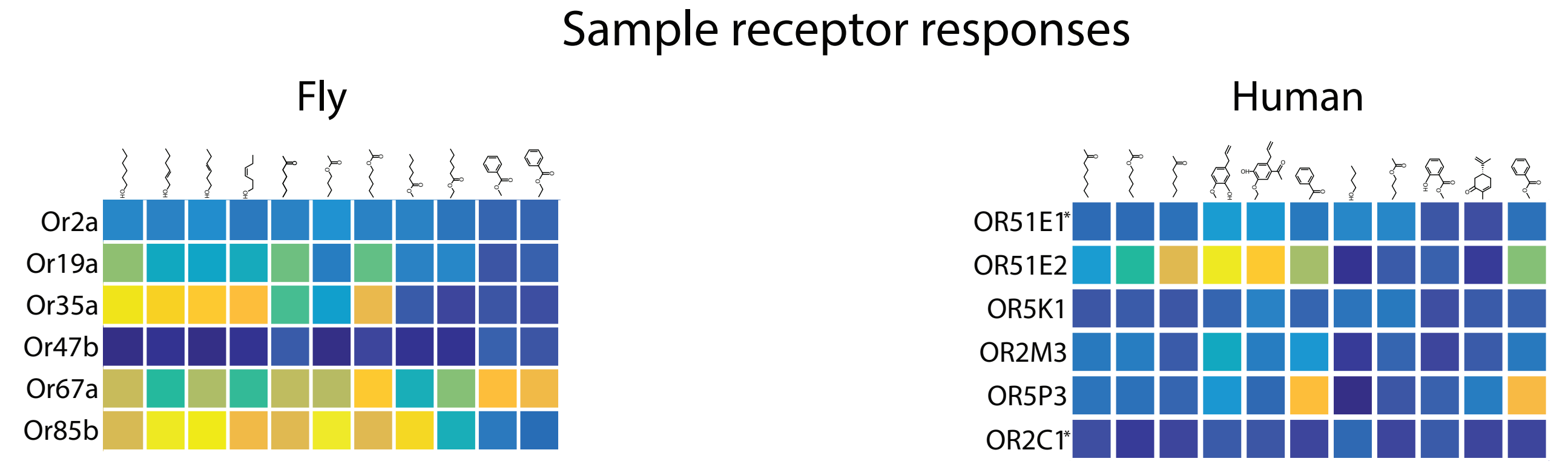
Tiberiu Teşileanu[1,2], Simona Cocco[3], Rémi Monasson[4], Vijay Balasubramanian[1,2]

[1]Initiative for the Theoretical Sciences, CUNY Graduate Center; [2]Dept. of Physics & Astronomy, University of Pennsylvania; [3]Laboratoire de Physique Statistique de l'ENS; [4]Laboratoire de Physique Théorique de l'ENS

Background

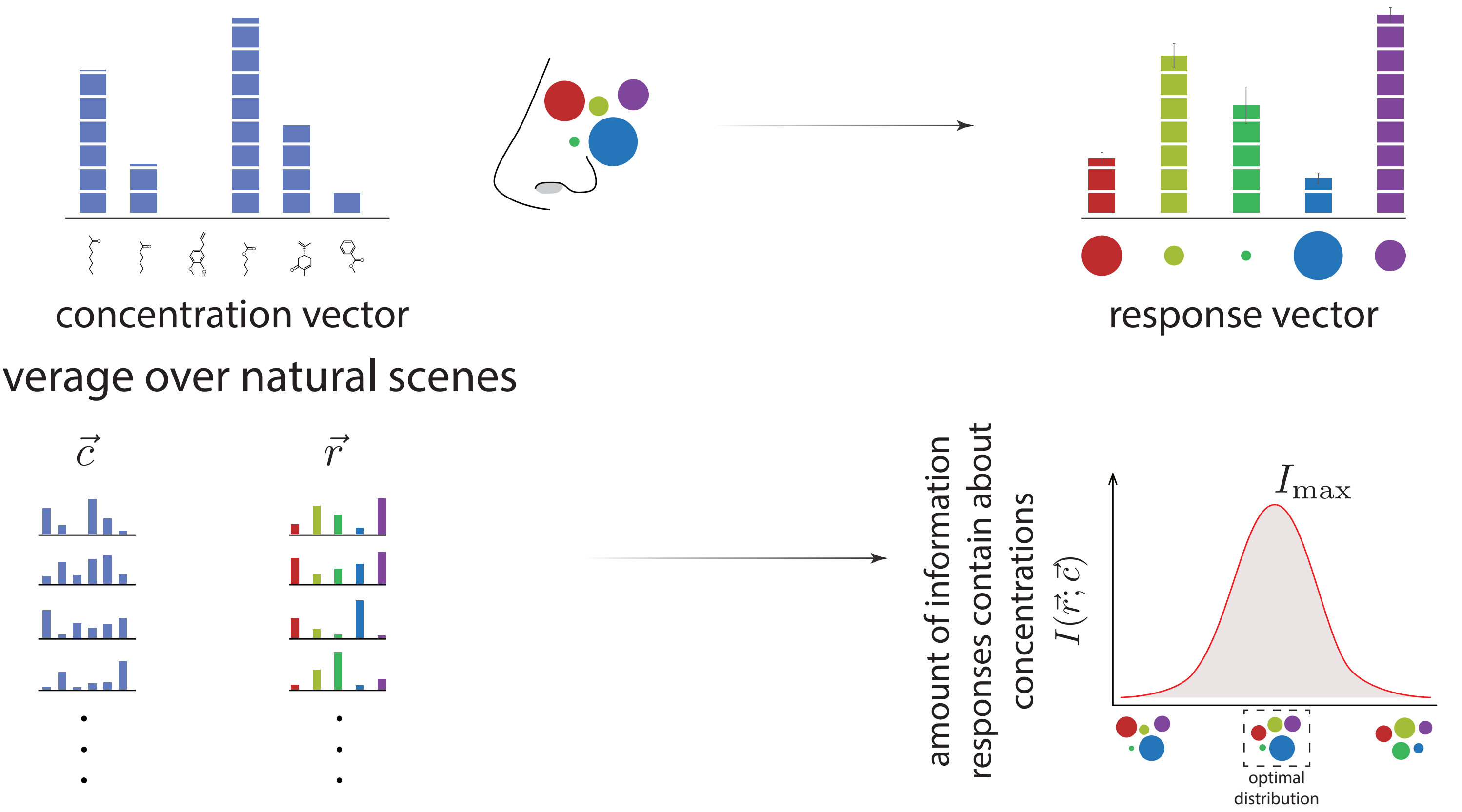
- olfactory sensory neurons (OSNs) express one receptor type per cell
- each receptor responds to many volatile molecules (odorants), and each odorant activates many receptors
- output from OSNs of a given type converge onto a glomerulus
- olfactory information sent to olfactory bulb and then to cortex
- architecture similar between vertebrates and invertebrates, despite very different receptor structure




Sample receptor responses

Outline

- abundances of different receptor types vary greatly
- differences in abundances can be species-specific
- distribution of receptor types in mammals is modulated by environment
- we propose that the distribution of receptor types is adapted to maximize the information passed to the brain about the kinds and concentrations of odorants in the environment
- this relates the abundances of different receptor types to the statistics with which odorants typically occur in natural environments



Model

Given odorant concentrations $\vec{c} = \{c_1, c_2, \dots, c_N\}$, we use a linear model to describe the glomerular responses $\vec{r} = \{r_1, r_2, \dots, r_M\}$:

$$r_a = \sum_i S_{ai} c_i + \frac{\eta_a}{\sqrt{K_a}}\,,$$

where S_{ai} are elements of the "sensing matrix", indicating how strongly receptor a responds to odorant i; K_a is the number of receptors of type a; and η_a is Gaussian noise with unit variance (different noise variances per receptor type can be absorbed in the scaling of the rows of S). Note that the responses are normalized by dividing through the number of receptors of each type, so that increasing the abundance of a given receptor type keeps its overall activity about the same, but reduces noise.

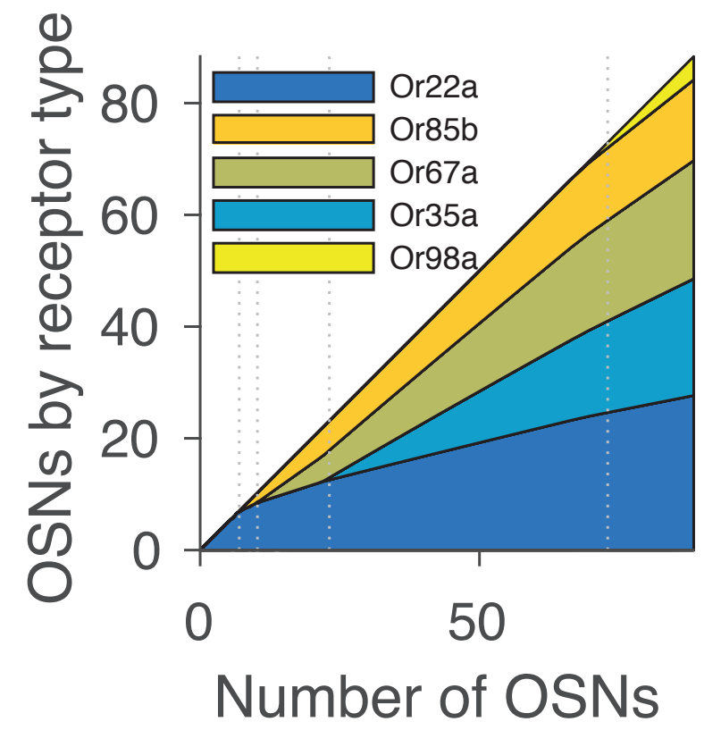
Modeling the natural statistics of odorant concentrations as a multivariate Gaussian with covariance matrix Γ, we can estimate the mutual information between concentrations and responses; we get

$$I(\vec{r};\vec{c}) = \frac{1}{2}\log\det\left(\mathbb{I}_N + \hat{S}^T \mathbb{K} \hat{S}\right)\,,$$

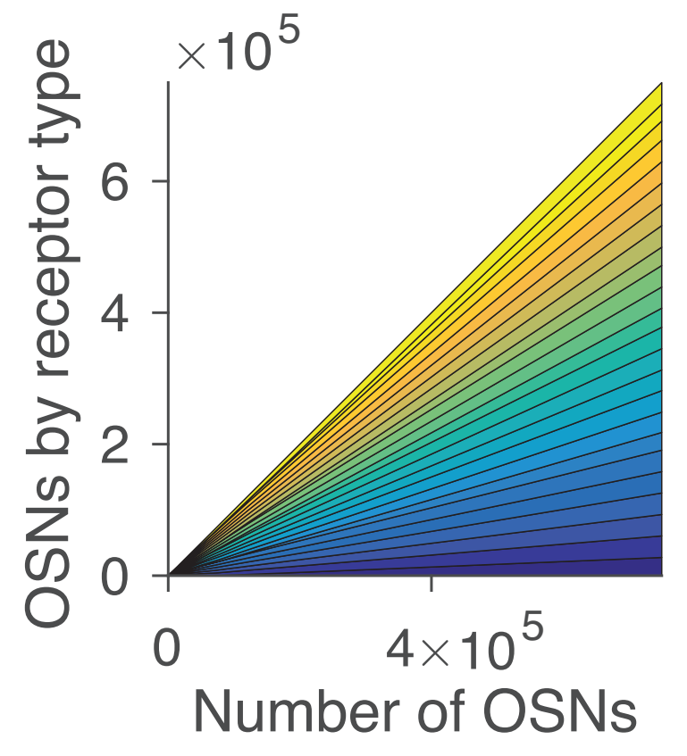
where $\mathbb{K}$ is a diagonal matrix whose diagonal entries are given by the receptor abundances K_a and $\hat{S} = S\Gamma^{1/2}$. We maximize $I(\vec{r};\vec{c})$ keeping the total number of receptors $K = \sum_a K_a$ constant.

Results

Dependence on number of olfactory neurons

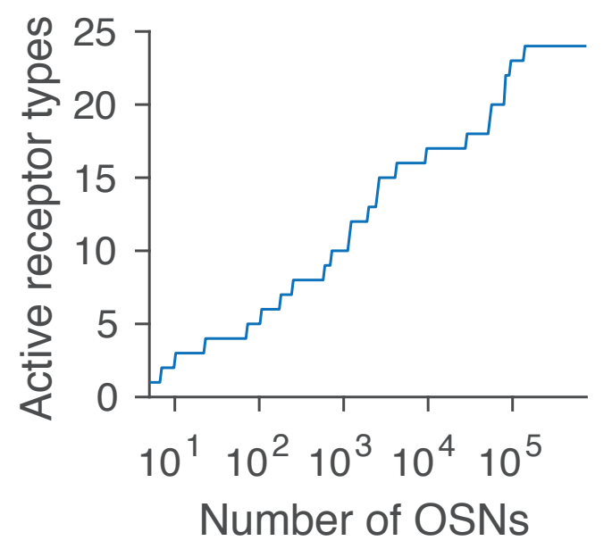


When the total number of olfactory neurons K is very small, it is most efficient to focus all neurons on a single receptor type, increasing the signal-to-noise ratio (SNR). As K increases, more receptors become expressed.



When the total number of olfactory neurons K is very large, noise becomes negligible, and the precise distribution of olfactory receptor types is less important. At the optimum, each type has an approximately equal share of the total.

Our framework predicts that increasing the total number of olfactory neurons should lead to an increase in the number of receptor types that are expressed.

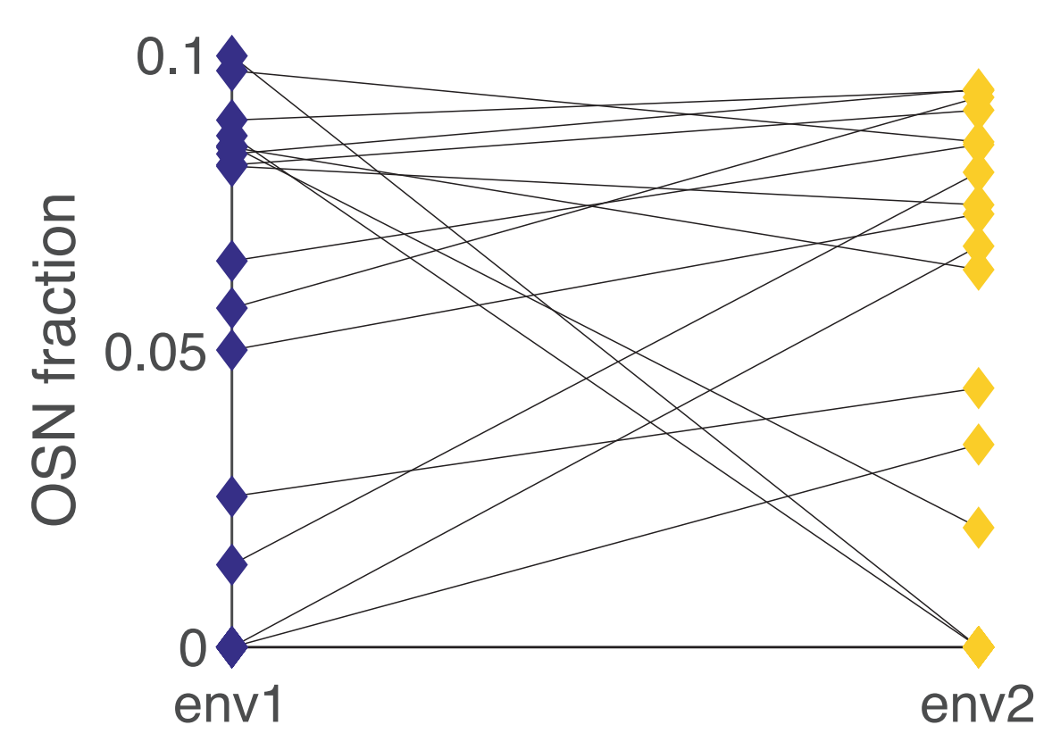


(sensing data above is based on measurements using fly receptors, (Hallem and Carlson 2006))

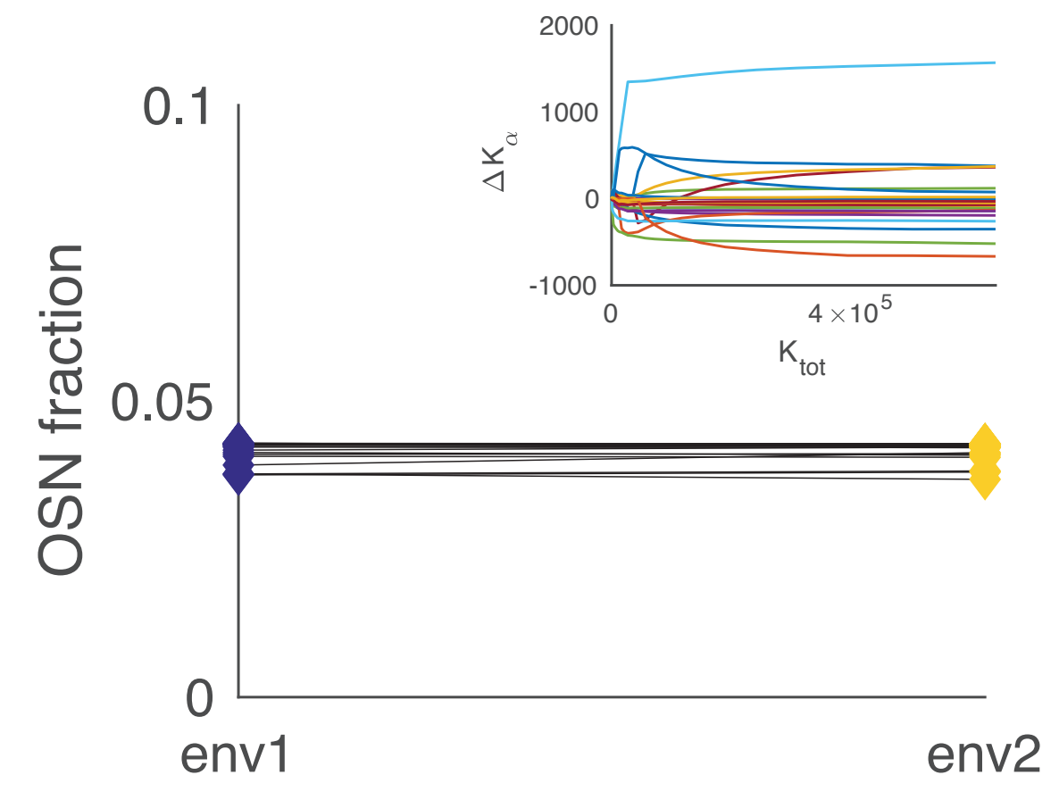
Results (continued)

Dependence on environment

The optimal distribution of olfactory neurons by receptor type depends on the olfactory environment through the covariance matrix Γ of odorant concentrations in natural scenes. This implies that in our model, a change in the environment is predicted to result in a change in the abundances of some receptor types.

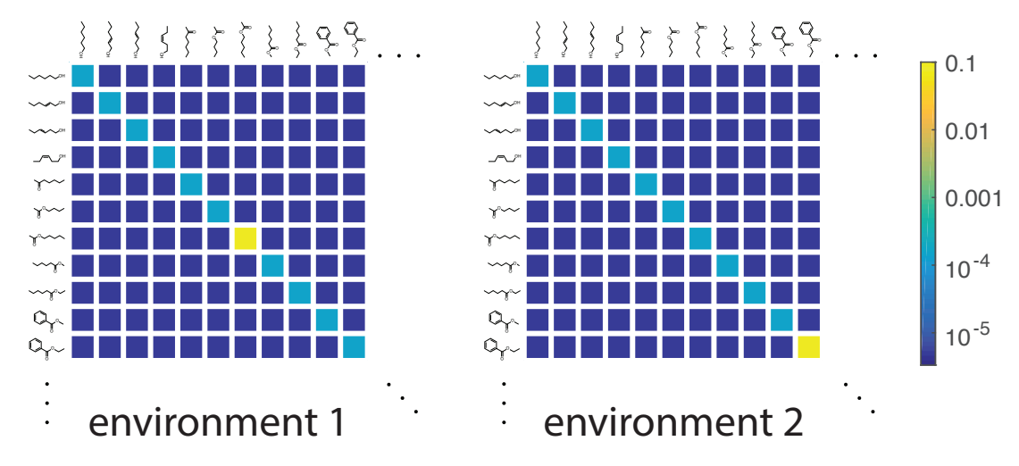


The effect of the environment is most pronounced when the SNR is moderate. In this case, many receptor types are affected by a change in environment, with some becoming more abundant, while others becoming less abundant.



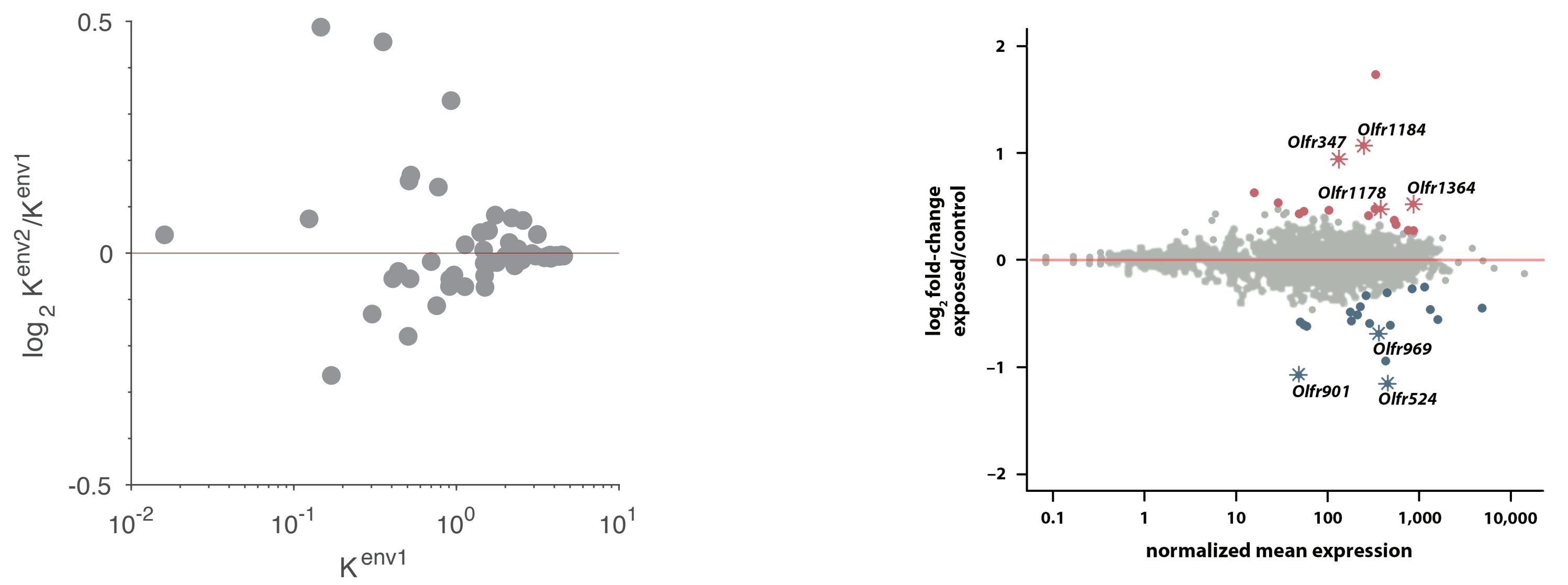
When the total number of olfactory neurons is so high that receptor noise becomes negligible, changes in environment affect the number of OSNs of each type, but have little influence on their fraction of the entire population of neurons.

Environments here differ in the set of odorants that fluctuate most. Both environments have uniform variance for other odorants, as well as uniform covariance between all odorants.



Mammalian data and comparison to experiment

Olfactory neurons in insects do not change during their lifetime. However, in mammals, sensory neurons in the olfactory epithelium get replaced every few weeks. This opens up the possibility that the distribution of receptor types can change during the lifetime of a mammal. Indeed, such changes have been observed, in addition to species-specific features of this distribution (Ibarra-Soria et al. 2016).



Log-ratio between receptor abundances in two different environments shown as a function of the abundance in the original environment. In the second environment, four odorants have increased variance (acetophenone, eugenol, heptanal, and R-carvone). **Left:** results from our model using sensing data based on measurements with human receptors, (Mainland et al. 2015). **Right:** values measured by (Ibarra-Soria et al. 2016) when mice were intermittently exposed to odorant mixture for 24 weeks.

Future directions

- design or measure realistic odorant covariance matrices
- use a more realistic model (e.g., Gaussian mixture) for the odorant distribution
- use nonlinear responses for the glomerular activities
- employ other noise models, e.g., sources of noise beyond receptor noise

References

Hallem, E. A., Carlson, J. R. (2006). Coding of odors by a receptor repertoire. Cell, 125(1), 143–160.

Ibarra-Soria, X., et al. (2016). Variation in olfactory neuron repertoires is genetically controlled and environmentally modulated. bioRxiv. https://doi.org/10.1101/074872

Mainland, J. D., et al. (2015). Human olfactory receptor responses to odorants. Scientific Data, 2, 150002. https://doi.org/10.1038/sdata.2015.2